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Lunar Base Thermoelectric Power Station Study

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Abstract. Under NASA's Project Prometheus, the Nuclear Systems Program, the Jet Propulsion Laboratory, Pratt & Whitney Rocketdyne, and Teledyne Energy Systems have teamed with a number of universities, under the Segmented Thermoelectric Multicouple Converter (STMC) program, to develop the next generation of advanced thermoelectric converters for space reactor power systems. Work on the STMC converter assembly has progressed to the point where the lower temperature stage of the segmented multicouple converter assembly is ready for laboratory testing and the upper stage materials have been identified and their properties are being characterized. One aspect of the program involves mission application studies to help define the potential benefits from the use of these STMC technologies for designated NASA missions such as the lunar base power station where kilowatts of power are required to maintain a permanent manned presence on the surface of the moon. A modular 50 kWe thermoelectric power station concept was developed to address a specific set of requirements developed for this mission. Previous lunar lander concepts had proposed the use of lunar regolith as in-situ radiation shielding material for a reactor power station with a one kilometer exclusion zone radius to minimize astronaut radiation dose rate levels. In the present concept, we will examine the benefits and requirements for a hermetically-sealed reactor thermoelectric power station module suspended within a man-made lunar surface cavity. The concept appears to maximize the shielding capabilities of the lunar regolith while minimizing its handling requirements. Both thermal and nuclear radiation levels from operation of the station, at its 100-m exclusion zone radius, were evaluated and found to be acceptable. Site preparation activities are reviewed and well as transport issues for this concept. The goal of the study was to review the entire life cycle of the unit to assess its technical problems and technology needs in all areas to support the development, deployment, operation and disposal of the unit.

INTRODUCTION

Recently, under NASA's Project Prometheus, the Nuclear Systems Program, the Segmented Thermoelectric Multicouple Converter (STMC) Development Program, JPL has lead a technical team in developing a new class of thermoelectric materials and technologies. The primary focus of the STMC Program over the past year has been the development and fabrication of the lower temperature multicouple (LTM) stage of the STMC converter using a conductively coupled generator design concept. JPL's efforts have also included identification of the potential upper stage thermoelectric materials; a task supported by more than a half-dozen U.S. university research laboratories. Major milestones achieved over this past year include 1) development of the processing and fabrication procedures to fabricate and test the LTM stage, 2) fabrication of six 8-couple test modules, and 3) identification and selection of the upper stage thermoelectric candidate materials and the start of material property characterization efforts (Fleurial 2006).

Pratt & Whitney Rocketdyne, with Teledyne Energy Systems, is under contract to JPL to provide systems integration support and converter fabrication expertise for the preparation of materials, components, subassemblies and fabrication of tooling for assembling and bonding the LTM stage converter. A parallel activity was initiated at Pratt & Whitney Rocketdyne to examine potential applications of this STMC technology for NASA designated missions, such as future lunar surface power applications in the kilowatt electric power range. This paper discusses one possible approach to providing a lunar base thermoelectric power station based upon the STMC program's LTM stage converter technology.

BACKGROUND

Prior to investigating potential concepts for a lunar base power system application, a set of ten requirements or ground rules were established to limit the scope of the study to near-term technologies availability and address manned-base operations. These requirements are shown in Table 1.

Table 1. Study Requirements

Initial studies involved a lunar lander concept using an instrument-rated radiation shield (or shadow shield) similar to a configuration for a deep space nuclear power system layout. Previous studies, under the SP-100 Program, (Mondt 1992), had reviewed this concept coupled to a "LEM-type" lunar lander stage to land the reactor power system in a meteor crater on the lunar surface. Power and control cables, more than a kilometer long, plus the power conditioning, control, and distribution (PCCD) subsystem hardware would then be deployed to the lunar habitat located over the rim of the crater on the lunar surface. Some of the later lunar base power station concepts, envisioned moving tons of lunar regolith "dust" around the perimeter of the reactor power system to provide a man-rated radiation shield to protect the lunar base astronauts from the reactor's radiation. This biological shield, made of piled-up regolith, has to be massive in size and it still only represents a "shadowed-shield" approach to providing radiation protection to the astronauts. Most concepts did not address the scattered gamma and neutron dose rates received at a manned base located less than a kilometer away. Earlier lunar base power studies, performed under the SNAP 8 Program in the 1960s, (Dieckamp 1967), had proposed to bury the reactor power system in the lunar soil, but a heavy containment vessel was required to encapsulate the entire power system making the packaged system too massive a unit to be transported and landed on the lunar surface. However, this approach did permit the radiation exclusion zone radius to be significantly reduced below a kilometer. Our conclusion from the review of the various early concepts for a lunar base reactor power system was that an under-shielded reactor power system represents a radiation hazard source to a man-rated environment. Therefore, the present concept for a manned lunar base reactor power system, configured for suspension within a man-made lunar surface cavity as illustrated in Figure 2, may be an alternate method of providing a lunar base with kilowatts of electrical power while maintaining a safe environment for the astronauts with a minimum exclusion zone radius of as little as 100 meters.

Figure 2. Lunar Base 50 kWe Thermoelectric Power Station

LUNAR SURFACE POWER STATION

The point design features of the power system concept were selected to be consistent with the requirements for the study. The power station is shown in its operating configuration in Figure 2 with its two large radiator assembly panels deployed out to a radius of 19.65 meters on either side of the station's vertical centerline. The total height above the lunar surface for these radiator assemblies and the station's central support structure is 4.26 meters. The lower manifolds for these radiators are located just 0.6 meters (~2 feet) above the lunar surface. Note that the entire power station is vertically-suspended on the four foot-pads in contact with the lunar surface. No other support is provided to the station except at these four locations.

The total depth of the station's lunar cavity is 5.5 meters with a 1.4 m inner diameter upper cavity to a depth of 4 meters and a 0.81 meter inner diameter lower cavity extending another 1.5 meters below the upper cavity. This location for the reactor assembly provides excellent radiation attenuation factors for this high power reactor application. The secondary shield located at the lunar surface provides additional attenuation of the neutron and gamma scatter dose rates at the exclusion zone radius. This configuration defines the requirements for the lunar surface cavity excavation task.

The power station schematic is shown in Figure 3, while the thermal balance is provided in Table 2. The liquid metal cooled reactor is rated at 1320 kWt for 7-years full power operation or 9.1 MW-yrs lifetime. Total fuel loading is 164 kg of UN with 93.15% enrichment. This limits the peak fuel burnup values to < 2.4% and the average fuel burnup value to ~1.5%. The power system's thermal requirement, at Beginning of Mission (BOM) conditions, is 1255 kWt to the hot side heat exchangers in the power conversion assemblies or PCAs. The primary heat transport loop temperature differential was optimized to 100 K drop using a NaK-78 coolant. The four TEM pumps in the four parallel PHT loops consume 40.6 kWt to drive the primary and secondary NaK loops and reject 38.5 kWt to the four heat rejection loops servicing the eight PCAs. The HRS loop temperature drop was also optimized at 100 K. The total heat rejected to the two radiator assemblies is 1198 kWt through 184 square meters of radiator panels deployed on both sides of the power station support tower. Each radiator assembly is equipped with two liquid inlet manifolds and two return manifolds to service one-half of the power station's heat rejection requirements. These radiators operate at a mean heat rejection temperature of 656 K and radiate into a sink temperature of 270 K. The lunar surface sink temperature is controlled by aluminized Kapton sheeting laid out on the lunar surface at the base of these radiators to reflect rather than absorb solar and thermal radiation in that immediate area.

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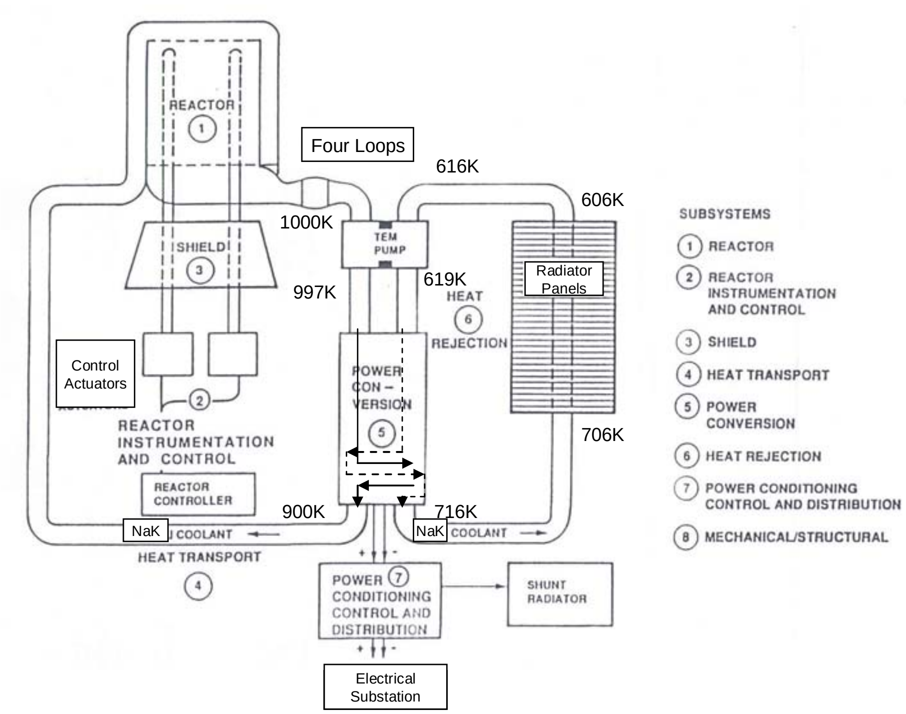

Figure 3. Lunar Base Thermoelectric Power Station Schematic

Table 2. TE Power System Thermal Balance

Parameter	Units	Value
Reactor rated thermal power	kWt	1320
BOM thermal power	kWt	1255
Lifetime	MWt-yrs	9.1
PHT loop temp. drop	K	100
PHT loop total flow rate	kg/s	14.452
TEM pumps thermal power	kWt	40.6
PGM thermal power	kWt	1214.1
PGM electrical power	kWe	56.54
PGM reject power	kWt	1160
TEM pumps reject power	kWt	38.5
Total HRS reject power	kWt	1198
HRS loop temp. drop	K	100
HRS loop total flow rate	kg/s	13.69
Total Radiator Area	m^2	184
Effective radiating temperature	K	656
Lunar sink temperature	K	270
Radiator panel fin efficiency		0.8
Rad. panel avg. thermal emissivity		0.8
PMAD power out (BOM)	kWe	54.3
PMAD voltage out (BOM)	V	159

The controlled voltage output of the station to the lunar base, at BOM conditions, is 54.3 kWe at 159 Vdc.
The reactor assembly, illustrated in Figure 4, contains 271 fuel elements. Each fuel element contains uranium nitride fuel with 96% theoretical density and 93.15% enrichment in U-235, a free standing rhenium liner, in a 316L SS clad assembly. Each fuel element contains a UN fuel column 70 cm in height with a 15 cm height for the fission gas plenum. The core assembly, including its 271 fuel elements and internal reflector elements, is held in place by two grid plates made of TZM. An inlet plenum directs the NaK-78 coolant into the core assembly for heating and an outlet plenum directs the coolant to the discharge nozzles. The reactor is designed with a high length to diameter ratio (L/D ~ 2.5) to establish an intrinsic subcritical condition under water immersion conditions to address launch safety requirements. Reactor instrumentation and control design is illustrated in Figure 5. A radial reflector control assembly, manufactured from beryllium, was selected to control the fast neutron leakage from the core. Four windows within the radial reflector assembly would open or close to control the reactor thermal power level. The positioning of each reflector movable control element would be controlled by a dedicated stepper motor drive assembly. A secondary reactor shutdown mechanism or SCRAM device would be incorporated into the radial reflector assembly to permit tilt-out of the reflector assembly halves for rapid shutdown of the reactor. These mechanisms would be spring loaded to tilt-out, and they would be reset to their control position by a dedicated stepper motor drive assembly located at the top of the primary radiation shield plug surface in the control drive gallery. Due to the relatively small cavity for the reactor, neutron reflection from the lunar soil/rock cavity walls may require the use of a borated SS liner/guard tank for the reactor cavity. The primary radiation shield stepped-plug geometry is illustrated in Figure 6. The gamma shield will be manufactured from W-alloy (2 cm thickness) with a 0.51 meter O.D located at the base of the reactor vessel. A second gamma shield made of W-alloy and 1 cm thickness and 0.85 cm O.D. would be located after the first step in the primary shield. The neutron shield will be cast LiH with a SS honeycomb mesh for enhanced heat transfer from the bottom of the shield to its top surface for cooling of the LiH. A single stepped-plug shield design with a 0.295 meters radial step size was selected. The shield assembly has an outer diameter of 1.30 m, a small O.D. of 0.71 meters and a overall thickness of 0.84 meters. Control drive mechanism rods penetrate the shield housing in 6 locations near the center of the shield. Six control drive motors are located on the upper surface of the shield assembly in a reactor controls gallery. The primary function of this shield is to reduce the neutron activation levels of the secondary coolant (NaK) in the power generation module or PGM. It also provides for a small safe approach distance for the astronaut operators at the lunar surface following reactor shutdown.

Figure 4. Reactor Assembly

Figure 5. Reactor Controls Assembly

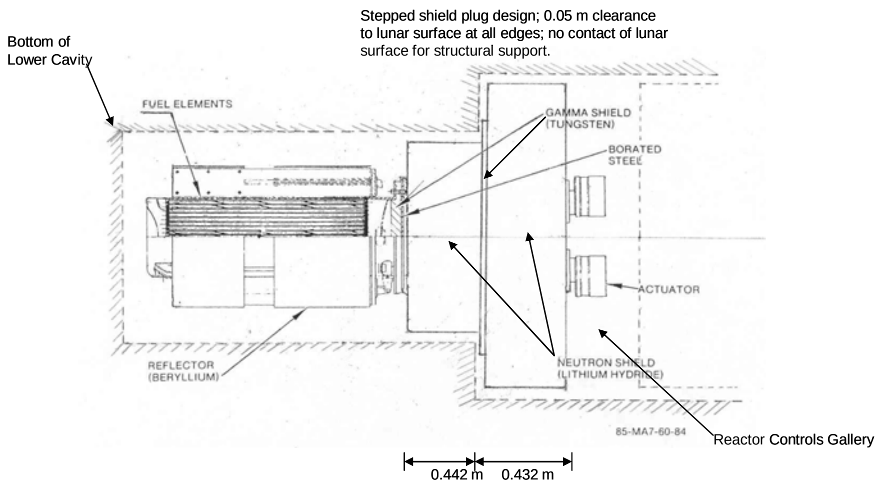

Figure 6. Primary Radiation Shield

Each primary heat transport (PHT) loop has a 100 K temperature drop by design. A twin throat dc pump configuration like that shown in Figure 7, with primary and secondary fluid throats electrically connected in series, was selected for the TE power station. This design was successfully testing in 1970 during the SNAP program and required fabrication of a flexible copper bus to connect the two pump throats. The present design would involve bonding CeFe4Sb12 and CoSb3 TE elements to the primary throat structure and the copper bus. In a TEM pump design, the flexible copper bus acts as an electrical path and a thermal shunt to deliver reject thermal power to the secondary throat which is cooled by secondary NaK returning from the radiators. The twin throat TEM pump for this application required 530 We at 5520 Amps. The thermoelectric open circuit voltage to drive the twin pump throats at this current level was 0.096 Vdc. The primary throat required 1700 Gauss magnetic flux density while the secondary throat required 2500 Gauss to achieve the required flow rates and pressure rise. Permanent magnets (Alnico 5-7) were selected to provide the magnetic field source based upon a minimum pump assembly mass. The pump throats are 0.4 meters in length which resulted in a pump assembly envelope of 0.66 m length, 0.4 m width and 0.26 m height. Four parallel primary heat transport loops service the reactor inlet and outlet plenums. Each PHT loop contains one twin throat TEM pump and two thermoelectric power conversion assemblies or PCAs. Each of the four PHT loops also contains a volume accumulator unit (VAU) to accommodate the differential thermal expansion between the primary NaK fluid and its containment boundary.

Figure 7. Thermoelectric Development Pump

Figure 8. Power Generation Module Layout

The Power Generation Module or PGM, illustrated in Figure 8, is designed to contain all of the power conversion and liquid metal handling hardware in a minimum envelope package with an outer diameter limited to 1.30 meters. The envelopes of the individual hardware items and their layout in the PGM are illustrated in the figure. The PGM contains four primary loop VAUs, four dual throat TEM pumps, eight power converter assemblies or PCAs, four heat rejection VAUs, and the interconnect piping, trace heaters and thermal insulation. The open truss support structure not only provides support for the PGM components but it is designed to bear the loads of the reactor / shield assemblies suspended from its forward end when vertically oriented. The mass estimate for the PGM is 1826 kg. Eight thermoelectric power conversion assemblies or PCAs, illustrated in Figure 9, generate the 56 kilowatts of electricity, at 166 Vdc, required from the PGM. Each PCA contains 12 planar counter-flow type heat exchanger sets with TE couples bonded to both sides of the hot side heat exchanger walls and two cooler heat exchangers bonded to the cold side of the TE couples. This assembly is known as the power converter module or PCM and is illustrated in Figure 10. The converter and PCM performance is summarized in Table 3, while the PCA and PGM performance is summarized in Table 4. The total steady-state power out from the PGM to the PCCD subsystem is 56.54 kWe at 165.7 Vdc.

Figure 9. Power Conversion Assembly

Figure 10. TE Power Converter Module

Table 3. Thermoelectric Converter Performance

Table 4. PCA and PGM Summary Performance

Parameter	Units	Value
PCA wiring harness layout		1P X 12S
PCA current	A	42.65
PCA voltage	V	165.7
PCA power	We	7070
PCA efficiency	%We/Wt	4.65
PCA thermal power in	kWt	151.76
PCA reject power	kWt	144.5
Load/Gen. Resistance ratio		1.215
PCA HX thermal eff.	%	99
PCA hot NaK flow rate	kg/s	1.806
PCA cold NaK flow rate	kg/s	1.711
PCA hot NaK pressure drop	psi	0.186
PCA cold NaK pressure drop	psi	0.46
Overall length	M	0.53
Width & Height	M	0.26
PGM wiring harness layout		8P X 1S
PGM Current	A	341.2
PGM voltage	V	165.7
PGM gross electrical	kWe	56.54
PGM thermal power	kWt	1214.1

The volume accumulator unit designs used in the power system and illustrated in Figure 11 were extensively developed during the SNAP Program. The VAU provides the overpressure on the working fluid to prevent boiling in the core outlet surfaces and provides positive NPSH at the TEM pump inlet to suppress cavitations of the working fluid. The primary heat transport loop VAUs are designed to accommodate 0.017 cubic meters each of primary NaK. This will provide for the net 20% fluid expansion differential as the primary loop reaches its operating temperatures. The heat rejection VAUs are designed to accommodate 0.0223 cubic meters of secondary NaK each. This expansion volume will accommodate a net 11% fluid expansion differential as the heat rejection loops reach their operating temperature.

Figure 11. Gas Backed Volume Accumulator Unit

Figure 12. Heat Rejection Radiator Assembly

The heat rejection subsystem is based upon a pumped-loop space radiator design developed under the International Space Station Program as illustrated in Figure 12. The ISS space radiators were based on ammonia coolant in an aluminum radiator panel. The higher operating temperature required for the thermoelectric power system's radiators will require higher temperature capable materials and a higher strength design. Four heat rejection NaK loops, driven by the secondary pump throats of the twin TEM pumps, service the eight PCAs. A 100 K loop temperature drop is maintained by these pumps. Waste heat is transported to two vertically oriented space radiator assemblies located 0.6 meters above the lunar surface. Each radiator assembly contains seven deployed radiator panels with an overall height of 3.66 meters. Each panel is 3.05 meters in height and 2.18 meters in width and .0175 meters in thickness. These panels are constructed of carbon-carbon (K1100) facesheets for the radiating surfaces. A titanium flow tube, 1.27 cm I.D., provides the flow passage for the NaK across the radiator panel. Each tube is surrounded by a thermal saddle made of POCO Foam which is bonded to the two facesheets. A Reticulated Vitreous Carbon (RVC) filler is bonded to the two facesheets to provide rigidity to the panel, thermal conduction between the saddle and facesheets and micrometeoroid protection to the tube. The panel specific mass is estimated at 6.5 kg/m^2 dry. A graphite honeycomb structure would be an alternate choice for the filler material. Each radiator panel assembly provides 1000 square feet (93 m^2) of radiating surface area when fully deployed. Each planar radiator assembly contains 2 loop distribution manifolds made from titanium tubing which supply and collect NaK to and from alternate flow tubes in each of the seven panels. Optimal spacing for these flow tubes was determined to be 0.01m. Each of the four titanium distribution manifolds are insulated with multi-foil insulation and bumper armored to reduce their probability of non-puncture or PNP.

The Power Conditioning, Control & Distribution or PCCD subsystem would be located at 30 meters from the centerline of the central cavity on the lunar surface. Since the transmission line voltage is provided by the PCA, a shunt regulator is used to provide the fine voltage control and shunt excess power through a parasitic load radiator also located in the vicinity of the PCCD module. A 28 Vdc emergency backup bus is supplied by batteries for system recovery operations. Power is distributed to the 100-meter exclusion zone radius (EZR) using eight pairs of 6 AWG lines plus two ground lines. The sequential shunt unit (SSU), shown in Figure 13, could be the basis of the design for the shunt regulator with two units providing redundancy for the bus voltage control function.

Two reactor controllers are provided in the PCCD. One controller is dedicated for reactor criticality and low-power system startup operations. This unit would contain all the instrumentation and sensor network monitoring functions for initial reactor startup. It is co-located with the PCCD hardware. A second reactor controller, hard-wired to the PCCD main controller, would be installed at the EZR perimeter to provide gross adjustments in thermal power level, emergency shutdown / system restart, and scheduled shutdown capabilities.

A secondary radiation shield would be located at the top of the cavity at the lunar surface. A low-temperature, borated hydrogenous material (like Poly-B 201) canned in SS would be placed over the top of the cavity to reduce scattered neutron and gamma dose rates from the structural elements located above the central cavity. A stainless steel honeycomb core structure within the secondary shield casement would provide heat rejection from the cavity to its upper surface for thermal radiation to space. A thermal emissivity coating with a high ε/α ratio would be applied to the upper surface of this shield to maximize its heat rejection capabilities and minimize its operating temperature. Table 5 summaries the mass of the various components, subsystems, and system for the modular 50 kWe thermoelectric lunar base power station. The initial mass estimate for the entire power station package was approximately 6500 kg.

Table 5. System Mass Summary

50 kWe TE Power System Mass Breakdown	
Subsystem/Component	**Mass kg**
Reactor	469
Reactor I&C	251
Launch / EOL Safety	40
Primary Radiation Shield	845
Secondary Shield	273
Primary Heat Transport	856
TE Power Conversion	496
Heat Rejection S/S	277
Main Radiator Assemblies	1868
Power Conditioning & Control	553
Main Support Structure	538
Power System Total	**6466**

TRANSPORT AND PACKAGING

A basic assumption, employed in the lunar base architecture, was that the landing site for cargo would not be located in the astronaut habitat area of the base for safety reasons. Therefore, some means of lunar surface transport of the power station package in its stowed configuration would be needed from the landing site to the station's installation site. The Transporter / Erector, illustrated in Figure 14, could be one method used to traverse the lunar terrain. The multi-wheeled, multi-axial vehicle would transport the lunar power station package, with its thermal blanket wrapped around its stowed configuration, to the prepared installation site. Electrical power would be supplied by on-board batteries to the Transporter's wheels for mobility and to its payload to maintain an internal temperature to prevent NaK freezing during its traverse to the installation site and during installation. At the prepared site, the Transporter / Erector would elevate its payload support platform into the vertical position for installation in the site receiver cavity. The partially installed power station is illustrated in Figure 15 from a top down view with its four support legs extended out to the lunar surface. The entire power station mass is supported on these four surface support pads. The two radiator assemblies are shown prior to their deployment in the stowed configuration. The central cavity outline is indicated in the figure to establish radiation scattering pathways to the exclusion zone radius for this configuration. Note that only the central support structure is directly in the streaming radiation path above the power station's reactor. The primary and secondary radiation shields attenuate the neutron and gamma source term coming from the reactor and cavity walls to the central support structure located above the lunar surface. (Johnson 2006) has evaluated the effectiveness of the shielding provided in the proposed concept. The estimated total dose rate, at the 100-meter exclusion zone radius, was estimated to be ~0.57 mRem/hr during operation of the power station. The thermal analysis of the additional heat flux at the EZR perimeter, due to the large flat panel, thermal radiators on the power station, indicated that less than 1.4% of the nominal solar flux at the site perimeter would be due to operation of these radiators.

Figure 14. Lunar Transporter / Erector

Figure 15. Top view of Power Station at lunar surface prior to radiator panel deployment.

The present concept is based upon a hermetically-sealed integrated nuclear power station package that would need to be transported on the lunar surface to a site prepared by the astronauts prior to its arrival. Figure 16 illustrates one possible packaging concept for the lunar Transporter/Erector and power station in a launch package configuration. A 4.6-meter payload fairing envelope is indicated in the figure. The Transporter supports the power station in this configuration and provides the electrical power for trace heating the liquid metal piping during the flight to the lunar surface and while on the lunar surface.

Figure 16. Power Station / Transporter packaged for launch

STATION SITE PREPARATION ACTIVITIES

The excavation of the site is defined by the dimensions of the power station's cavity. With a depth of 5.5 meters and an internal diameter of 1.40 meters for the cavity, approximately seven cubic meters or 245 cubic feet of lunar regolith would have to be removed to form the interior dimensions of the cavity. Within a few inches of the lunar surface, it was assumed that a basalt-like rock would have to be removed by the excavation hardware. While there may be several methods of performing this task, one of the least energetic methods of excavating the cavity would include a rock boring apparatus coupled with an auger as depicted in Figure 17. Known as an LPET or Lunar Power

Entrenchment Tool, this is shown in the figure as a lander concept, but it could be incorporated into a wheeled vehicle concept as well. The LPET would use on-board fuel and oxidizer tanks and a gas generator turbo-alternator set to produce power for a dc electric motor drive on the rock boring/auger apparatus. This concept is similar to a tunnel boring machine used terrestrially, except the “tunnel” is in a vertical orientation in the lunar site case. A metal casement, made of titanium alloy, may be required to reinforce the cavity walls during the boring and regolith removal operations. Dry lubricants like molybdenum disulfide or a graphite/glycerin may be needed in the lunar excavation process. New materials would have to be evaluated for these purposes. In (Harvey 1989), a five centimeter diameter drilling apparatus was designed for remotely extracting core samples on a future robotic mission to the lunar South Pole region. Based on this work and the work in earlier NASA reports, a preliminary estimate of the excavation task involved in the lunar cavity case suggests that a 50 kWe drive motor with a boring head speed of ~120 rpm could excavate the 1.4 m diameter cavity down to a depth of 5.5 m in less than 100 hours with some margin to spare. The overall feasibility of a larger boring machine, operating on the lunar surface, remains to be further refined in future studies.

Figure 17. Lunar Power Entrenchment Tool (LPET) Lander

CONCLUSIONS

The basic elements of a 50 kWe modular, thermoelectric power station for lunar surface operation over a 7-year period have been identified. The STMC program’s LTM stage formed the basis of the power conversion subsystem for the power station. Component technologies taken from the previous SNAP program and the ISS electrical power subsystem can be synergistically used to support a lunar base power station. The concept of suspending the power station over a prepared, man-made lunar cavity appears to be plausible, but it will require future defining studies for its refinement. Results from some initial assessments indicate that the thermal and radiation induced environments may be acceptable for a 100-meter exclusion zone radius at a lunar base site using this approach.

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